12-2016

Tracking of Human Joints Using Twist and Exponential Map

Xiaodong Yang
University of Tennessee, Knoxville, shaddadi@vols.utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Xiaodong Yang entitled "Tracking of Human Joints Using Twist and Exponential Map." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

Jindong Tan, Major Professor

We have read this thesis and recommend its acceptance:

Eric R. Wade, Xiaopeng Zhao

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Tracking of Human Joints Using Twist and Exponential Map

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Xiaodong Yang

December 2016

This thesis is dedicated to my parents.

Acknowledgements

I would like to express the sincere thanks to my advisor, Dr. Jindong Tan, for his guidance and support in the past two years. I would like to thank Dr. Eric R. Wade and Dr. Xiaopeng Zhao who served as my committees members and provided suggestions on my thesis.

I would like to thank all my labmates at the University of Tennessee: Dr. Hongsheng He, Dr. Xiaolong Liu, Ning Li, Yan Li, Reza Yazdanpanah and Zhe Su. I appreciate their encouragement and help on my research and my daily life.

Finally, I would like to thank all my family members who always support, encourage and love me.

Abstract

Motion tracking system in the home-based environment exhibits attractive advantages for stroke patients. Current methods suffer from incapability of accurately tracking movements with high degree of freedoms. Besides hardly meeting the predefined position during inertial sensor mounting also affects system's performance.

To tackle these challenges, a motion tracking system using twist and exponential map technology is developed in this paper. Firstly, a kinematic model for trunk and upper extremity is designed. Based on this model, twist and exponential map method which updates frames in their initial coordinates instead of transforming coordinates from one frame to another presents high efficiency and convenience in estimating joints' position and orientation. In the experiment, multiple movements are tracked by both of inertial sensor system and optical tracking system. Their comparison verifies this system's high accuracy.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Human Motion Analysis

Wearable motion-tracking system has attracted more and more attention because of its wide applications as figure 1.1 shows. Among these applications, 3D human model is essential for monitoring rehabilitation of the motor-deficit disease such as Parkinsons Disease and post stroke which increasing population of the elderly are suffering from. The goal of rehabilitation is to ensure patients who undergo motor deficits to regain the highest possible level of motors by performing various activities and physical exercises. In order to achieve adequate and reliable motion data in the dynamic process of rehabilitation and avoid incorrect severity estimation and improperly exercising in the long-term rehabilitation, continuous and accurate movement supervision in the home-based environment is required.

Current algorithms used for motion tracking are mainly based on robotic platform, visual tracking and inertial sensors. In robotic platform systems, the exoskeleton is installed to the participants limbs to perform several movements. Although they could achieve high accuracy, the high cost and cumbersome properties hinder their application into ambulatory environment. Visual tracking system can achieve highly accurate 3D human model by detecting and reconstructing reflective markers attached

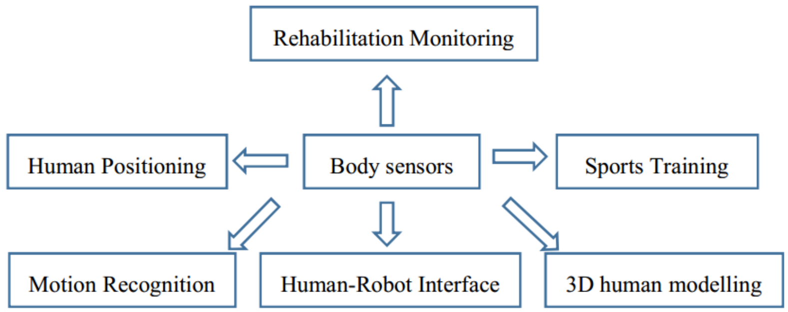


Figure 1.1: Application of Inertial Tracking System

to limbs from different perspectives. However they are expensive and affected by makers lose and occlusion. While inertial sensors are wearable, low cost and good accuracy which make them appropriate a choose to track human's activities.

1.2 Motivation and Challenges

Among the monitoring system, inertial motion tracking systems have become an effective tool to monitor and analyze rehabilitation from injury, fall detection, enhancement of disorders,clinical gait analysis and many other biomedical areas. This typical technique is based on the inertial measurement unit (IMU), which is a low cost and wearable sensor consisting of a triaxial accelerometer, a triaxial gyroscope and a triaxial magnetometer. They are portable and able to monitor human activity in home-based environment over a long time. It could provide more comprehensive and direct motion information, especially the complicated motions with high degrees of freedom, than the methods based on single accelerometer and gyroscopes.

Traditional inertial tracking systems are usually suffering from the inability of tracking motions with high degrees of freedom. Besides the sensors' predefined direction and position on the local segment would not be perfectly matched in the experiments, which leads to the accuracy's variation. Therefore developing a tracking system that has simple calibration and low computation and arbitrary direction and position on the segment could be the challenges.

1.3 Research Goals

This project aims to design an inertial motion-tracking system with high accuracy and capable of tracking complicated motions. The sensors position and direction on the segment can be arbitrary in the systems calibration. 3D motion and joint angels could be generated during this systems performing.

1.4 Contribution

The major contribution of this thesis is that we succeed to address the challenges aforementioned. An wearable inertial motion tacking system which is capable of accurately tracking complicated motions with high degrees of freedom has been designed. In this system, five IMU sensors are respectively attached to the waist, chest, upper arm and lower arm. An robotic manipulator is proposed to model the human anatomical structure. With this model, twist and exponential map technology is applied to analyze joints' kinematics. Compared with the traditional methods, this proposed method is able to continuously update each multi-joint's position in the global frame and accurately estimate their rotations. This system also has a simpler initialization process, which greatly increase the feasibility of serving the people with disabilities.

Chapter 2

Tracking of Human Joints Using Twist and Exponential Map

2.1 Introduction

There are around 6.8 million Americans suffering from stroke and there will be additional 3.4 million victims by 2030 Go et al. (2014). Large healthcare services and some effective rehabilitation strategies are required to help patients regain maximum movement skills. To address this huge demand, home-based rehabilitation can be an effective alternative for the patient discharged from hospital. It not only reduces remarkable cost, but also shortens the length of hospital stay and achieves more mental support related to individual needs from home based environment Anderson et al. (2000).

The wearable motion-tracking system exhibits an effective performance for these requirement. It can well monitor human joint's kinematics where the characteristics of motor-deficit diseases are directly presented. In order to achieve adequate and reliable motion data in the dynamic process of rehabilitation and avoid incorrect severity estimation and improperly exercising in the long-term rehabilitation, convenient and accurate movement supervision in the home-based environment is required.

Wearable motion-tracking systems are mainly robotic platform based, visual tracking based and inertial sensors based. In robotic platform systems, exoskeleton is installed to the participants limbs to perform several movements. Although they could achieve high accuracy, the high cost and cumbersome properties hinder their application into ambulatory environment. Visual tracking system can achieve highly accurate 3D human model by detecting and reconstructing reflective markers attached to limbs from different perspectives. However, they are expensive and easily affected by makers lose and occlusion. While inertial sensors are wearable, low-cost and high accuracy, making them an appropriate choice to track human's activities.

Traditional motion tracking systems with inertial sensors focus on accurately estimating segment's orientation and position by reducing the cumulative error caused by integration of angular velocity and double integration of acceleration. Giansanti et al estimated body segment's orientation and position by combining the acceleration and gyroscope Giansanti et al. (2005). Yun et al proposed an extended Kalman filter to estimate limb's orientation Yun and Bachmann (2006). The gyroscope, accelerometer and magnetometer are involved in their algorithm. Biomechanical constraints and optimization technologies were also utilized to achieve body segment's orientation with high accuracy Zhou et al. (2008). However, joints' kinematics are not clearly analyzed.

There exists works that focus on the analysis of knee joint kinematics with inertial sensors because of the less complicated anatomical structure. Copper et al analyzed the knee's flexion and extension rotation with two IMU sensors mounted on the thigh and shank. The combination of Kalman filter and anatomical constraints were adopted to improve system's accuracy Cooper et al. (2009). Favre et al also estimated knee joint's rotation by aligning two inertial sensors on adjacent segments and adopting fusion algorithm Favre et al. (2008). But methods capable of monitoring more comprehensive movements are still deficient.

Some research on upper extremity tracking have been done. Perez et al designed a 6-DoF upper limb model by assigning four inertial measurement units (IMUs) to the back of subjects, upper arm, forearm and hand Pérez et al. (2010). The direction and position of sensors were predefined so that rotations in the shoulder and elbow could be directly calculated form sensors roll, pitch and yaw achieved with rotation matrix. The prerequisite of sensor mounting could substantially reduce the complexity to calculate the joint angles. However, the system's accuracy would greatly rely on sensor configuration and would be unstable.

To avoid the cumulative errors during calculating orientation due to integration, Mahmoud et al El-Gohary and McNames (2012) proposed a method based IMUs. They designed a kinematic model for robotic arms and utilized Newton-Euler equations and the unscented Kalman Filter to continuously reduce noise and estimate the upper limb's movement. However complex movements involving more than one DoF each time is not explored. Another limitation is that rotation angle would be easily overestimated or underestimated due to the shoulder joint's displacement.

In this paper, a whole body tracking system based on our previous work is proposed Chen et al. (2014) to overcome aforementioned limitations. To clarify the joints' rotation in waist, shoulder and elbow, we firstly design a human kinematic model for upper extremity and trunk composed of revolution joints and rigid bodies. Twists and exponential map technology is applied to analyze body segment's kinematics. Since it only considers the relative orientation with respect to the sensors' initial configuration on human body, sensor mounting position will not have an effect on system's performance. Additionally, this characteristic clearly demonstrates a mathematic relationship between sensor's orientation and joint rotations, making it easier for rotation calculation. We then investigate system's accuracy by comparing its estimated joint angles with those obtained through optical tracking system.

2.2 Human Kinematic Model

For the human's kinematic model, the human anatomical structure proposed by the International Society of Biomechanics (ISB) is simplified to reduce system's complexity Wu et al. (2005). Human upper limb consists of upper arm, forearm and hand which has 10 degrees of freedom (DoFs) in total. The shoulder is regarded as a ball-and-socket joint with 3 DoFs. The rotation angles are composed of flexion-extension, internal-external and abduction-adduction rotations. The elbow joint is regarded as two hinge joints with 2 DoFs: flexion-extension and pronation-supination rotations. The Orientation of spinal movements would be considered as some rotations in waist joints with 3 DoFs.

A kinematic model for upper extremity including waist joint is designed as the Figure 2.1 shows. It includes 4 rigid bodies, i.e., chest, upper arm, lower arm and pelvis. It has 8 DoFs in total which are represented by θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, θ_7 and θ_8. The model is also applicable to lower extremity, because it has similar but less complicated anatomical structure. The items l_{wn}, l_{ns}, l_{se} and l_{ew} denote each segment's length. Body frame B is assigned to the pelvis' center as a global reference frame for all the movements. Body frame's direction is chosen according to two human anatomical planes: sagittal plane and coronal plane.

Four IMU sensors S_{ch}, S_{up} S_{low} and S_B sharing the same global frame determined by the gravity field and earth magnetic field are mounted on the rigid bodies to monitor their orientations, as Figure 2.1 indicates. The IMU sensor and its corresponding body segment are regarded as one rigid body so that the body segment's orientation can be represented by sensor's quaternions. Then rotation angle θ and unit axis vector ω can be extracted by

$$\theta = 2 \times \arccos q_0$$

$$\omega = \begin{cases} \frac{[q_1, q_2, q_3]^T}{\sin(\theta/2)} & \theta \neq 0 \\ [0, 0, 0]^T & \theta = 0 \end{cases} \tag{2.1}$$

where q_0, q_1, q_2 and q_3 are the four elements of a quaternion.

Since frame B is the global reference frame, all the representation of motions in global frame need to be converted into the body frame. To determine body's frame,

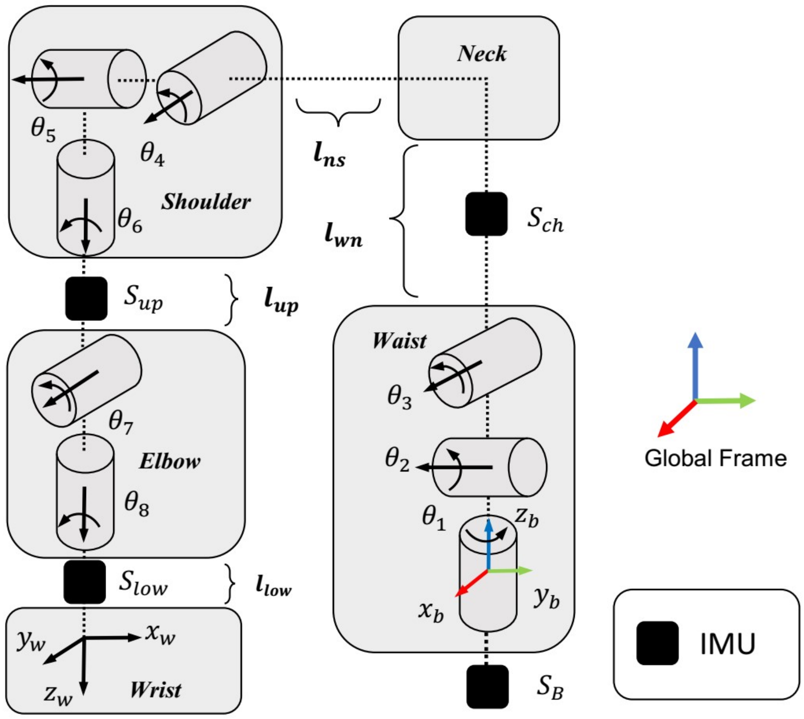


Figure 2.1: Kinematic Model for Upper Extremity and Waist Joint

participants with sensors mounted on are asked to stand straight and hold their arm vertical to the ground and then perform shoulder joint's pronation-supination rotation. The axis of rotation relative to the initial posture will be set as the y axis of frame B. The opposite direction of the gravity is selected as its z axis. After achieving the initial Body frame $[X_b^g \ Y_b^g \ Z_b^g]^T$, the initial rotation matrix of global frame relative to body frame can be calculated by

$$^{init}R_g^b \left[X_b^g \quad Y_b^g \quad Z_b^g \right]^T = I \tag{2.2}$$

We convert the matrix $^{init}R_g^b$ to quaternion $^{init}q_g^b$ and estimate the relative quaternion between body frame and its corresponding sensor $S_{\mathbb{B}}$ using

$$q_{s_{\mathbb{B}}}^b = {}^{init}q_g^b \otimes {}^{init}q_{s_{\mathbb{B}}}^g \tag{2.3}$$

where $q^b_{s_{\mathbb{B}}}$ and $q^g_{s_{\mathbb{B}}}$ respectively denotes sensor $s_{\mathbb{B}}$'s quaternion with respect to body frame and global frame and $\otimes$ denotes Hamilton product. Quaternion $q^b_{s_{\mathbb{B}}}$ is used to update body frame's orientation q^b_g during human activities. The sensor's reference frame can be transfered to the body frame by

$$q^b_* = q^b_g \otimes q^g_* \tag{2.4}$$

where $*$ denotes certain body segment.

To determine the initial configuration of the kinematic model, we assume that all body segments are along the gravity direction during the initial posture. Based on this assumption, joints' initial position p^{init}_s, p^{init}_e and p^{init}_w with reference to the body frame would be $[0, -l_{ns}, l_{wn}]^T$, $[0, -l_{ns}, (l_{wn} - l_{up})]^T$ and $[0, -l_{ns}, (l_{wn} - l_{up} - l_{low})]^T$. Let ${}^{init}q^b_{ch}$, ${}^{init}q^b_{up}$ and ${}^{init}q^b_{low}$ denotes body segments' initial orientation,i.e, the initial configuration of forward kinematics. Sensor's orientation change ${}^{r}q^b_*$ with respect to the initial configuration will be

$${}^{r}q^b_* = q^b_* \otimes ({}^{init}q^b_*)^{-1} \tag{2.5}$$

from which the unit rotation axis ω^r_* and angle θ^r_* can be achieved.

2.3 Calculation of Joint Position

2.3.1 Twist and Exponential Map

The general rigid body's motion can be represented by rotation and translation. The space of rotation matrix is given by

$$SO(3) = \{R \in \mathbb{R}^{3\times 3} : RR^T = I, detR = 1\} \tag{2.6}$$

Any orientation in space could be expressed by a rotation angle $\theta \in \mathbb{R}$ and a unit vector $\omega \in \mathbb{R}^3$ around which the rotation occurs. The orientation can also be expressed in matrix exponential using *Rodrigues' formula*:

$$
\begin{aligned}
R(\theta, \omega) &= e^{\hat{\omega}\theta} \\
&= I + \hat{\omega}\sin(\theta) + \hat{\omega}^2(1 - \cos(\theta))
\end{aligned}
\tag{2.7}
$$

where matrix $\hat{\omega}$ is a skew-symmetric matrix translated from $\omega \in \mathbb{R}^3$ and $\hat{\omega} \in so(3)$.

$$
\hat{\omega} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}
$$

$$
so(3) = \{S \in \mathbb{R}^{3\times 3} : S^T = -S\}
$$

For the motion including translation, let $R_{AB} \in \mathbb{R}^{3\times 3}$ be the orientation of frame B relative to frame A and $P_{AB} \in \mathbb{R}^3$ be the translation vector of the origin of frame A relative to the origin of frame B. The pair (P_{AB}, R_{AB}) composes the system's configuration. Let $SE(3)$ denote its configuration space which is the product space of $\mathbb{R}^3$ with $SO(3)$ Murray et al. (1994).

$$
\begin{aligned}
SE(3) &= \{(p, R) : p \in \mathbb{R}^3, R \in SO(3)\} \\
&= \mathbb{R}^3 \times SO(3)
\end{aligned}
\tag{2.8}
$$

A 4×4 matrix $\hat{\xi}$ is defined to convert traditional kinematics analysis into the homogeneous coordinates.

$$
\hat{\xi} = \begin{bmatrix} \hat{\omega} & v \\ 0 & 0 \end{bmatrix} \in \mathbb{R}^{4\times 4}
$$

$$
se(3) = \{(v, \hat{\omega}) : v \in \mathbb{R}^3, \hat{\omega} \in so(3)\}
$$

where $v = -\omega \times q$ and q denotes the rotation center. Elements of $se(3)$ are referred as twists.

The homogeneous transformation for a twist is given by

$$e^{\hat{\xi}\theta} = \begin{cases} \begin{bmatrix} e^{\hat{\omega}\theta} & (I - e^{\hat{\omega}\theta})(\omega \times v) + \omega\omega^T v\theta \\ 0 & 1 \end{bmatrix} & \omega \neq 0 \\ e^{\hat{\xi}\theta} = \begin{bmatrix} I & v\theta \\ 0 & 1 \end{bmatrix} & \omega = 0 \end{cases} \tag{2.9}$$

The orientation form $e^{\hat{\omega}\theta}$ and $e^{\hat{\xi}\theta}$ are slightly different from the traditional rotation matrix and homogeneous transformation matrix. They transform points in their initial coordinates rather than mapping them from one frame to another frame. The forward kinematics of a chain of joints can be formalized as

$$g_{st}(\theta) = e^{\hat{\xi}_1\theta_1} e^{\hat{\xi}_2\theta_2} \cdots e^{\hat{\xi}_n\theta_n} g_{st}(0) \tag{2.10}$$

where $g_{st}(0)$ represents the initial configuration of end effector's orientation in the initial frame and $g_{st}(\theta)$ represents the final configuration with reference to the initial frame. Matrix $\hat{\xi}$ starts from waist joint to wrist joint.

Compared to the forward kinematics analysis using Denavit-Hartenberg convention, the twist and exponential map method only needs frames for end effector and the base rather than for each revolution joint. Besides, the end effector's orientation change can be directly represented by its inertial sensor's measurement because the presented method only considers frame's relative orientation change with respect to its initial position. Therefore, the sensors' predefined mounting position for determination of their orientation relation with rigid bodies can be avoided.

2.3.2 Joints' Position Calculation

In this section, the position calculation of shoulder joint, elbow joint and wrist joint will be demonstrated. The initial position of the kinematic model has been derived above. The rotation axis ω in the forward kinematics equations only depend on the initial posture, independent of changes caused by some rotations. Each joint's center is chosen as the rotation center. Then the matrix $\hat{\xi}$ for each rotation is determined.

The forward kinematics for the position of shoulder joint p_s is achieved by

$$q^r_{ch} \Longrightarrow \{\theta^r_{ch}, \omega^r_{ch}\}$$

$$p'_s = e^{\hat{\xi}_1\theta_1} e^{\hat{\xi}_2\theta_2} e^{\hat{\xi}_3\theta_3} p^{init}_s$$

$$e^{\hat{\omega}^r_{ch}\theta^r_{ch}} = e^{\hat{\omega}_1\theta_1} e^{\hat{\omega}_2\theta_2} e^{\hat{\omega}_3\theta_3} \tag{2.11}$$

Since their rotation axis intersect at the origin of body frame, there would be no translation in trunk's movements. The shoulder joint's position can be simplified to:

$$p'_{s_{(3\times1)}} = e^{\hat{\omega}^r_{ch}\theta^r_{ch}} p^{init}_{s_{(3\times1)}} \tag{2.12}$$

The orientation of upper arm is the product of waist and shoulder joints' rotations. The translation is the shoulder joint's position p'_s.

$$q^r_{up} \Longrightarrow \{\theta^r_{up}, \omega^r_{up}\}$$

$$e^{\hat{\omega}^r_{up}\theta^r_{up}} = \prod_{i=1}^{6} e^{\hat{\omega}_i\theta_i}$$

$$p'_e = \prod_{i=1}^{6} e^{\hat{\xi}_i\theta_i} p^{init}_s = \begin{bmatrix} e^{\hat{\omega}^r_{up}\theta^r_{up}} & p'_s \\ 0 & 1 \end{bmatrix} (p^{init}_e - p^{init}_s) \tag{2.13}$$

Following the same idea, the orientation of lower arm can be achieved by combining aforementioned joints. The translation of lower arm's movement will be elbow joint's position p'_e. So wrist joint's position p'_w can be obtained by

$$q^r_{low} \Longrightarrow \{\theta^r_{low}, \omega^r_{low}\}$$

$$e^{\hat{\omega}^r_{low}\theta^r_{low}} = \prod_{i=1}^{8} e^{\hat{\omega}_i\theta_i}$$

$$p'_w = \prod_{i=1}^{8} e^{\hat{\xi}_i\theta_i} p^{init}_w = \begin{bmatrix} e^{\hat{\omega}^r_{low}\theta^r_{low}} & p'_e \\ 0 & 1 \end{bmatrix} (p^{init}_w - p^{init}_e) \tag{2.14}$$

In the whole process of joint position calculation, only joint rotations with reference to the initial posture need to be considered, which avoid the predefined sensor's position and orientation and guarantee arbitrary sensor mounting. Additionally the equations based on exponential map and twist also provide convenience for joint angle's calculation.

2.4 Calculation of Joint Angles

The main idea of rotation calculation is to utilize two articulate segments' orientations to calculate their relative orientation which is caused by their joint's rotation. Equations 2.11, 2.13 and 2.14 already clearly indicated their mathematic relation. Combining with active range of joint motion from reference Norkin and White (2009), joint angles could be eventually determined.

2.4.1 Calculation of Waist Joint Rotation θ_1, θ_2 and θ_3

Waist joints θ_1, θ_2 and θ_3 are directly associated with chest's orientation. The relative rotation matrix between pelvis and trunk can be calculated by combining equation (2.7) and equation (2.11), as equation (2.15) shows. The range of rotation θ_1, θ_2 and θ_3 are respectively set to $[-90^o, 90^o]$, $[-90^o, 45^o]$ and $[-45^o, 45^o]$. Elements in the first column and third row of the rotation matrix are chosen to calculate the joint rotations.

$$e^{\hat{\omega}^r_{ch}\theta^r_{ch}} = \begin{bmatrix} c_1c_2 & -c_3s_1 - c_1s_2s_3 & s_1s_3 - c_1c_3s_2 \\ c_2s_1 & c_1c_3 - s_1s_2s_3 & -c_1s_3 - c_3s_1s_2 \\ s_2 & c_2s_3 & c_2c_3 \end{bmatrix} \tag{2.15}$$

where c denotes cos function and s denotes sin function.

2.4.2 Calculation of Shoulder Joint Rotation θ_4, θ_5 and θ_6

Concatenated by the shoulder joint, joint's rotations are related with the orientation of upper arm and trunk. It can be achieved by transforming equation (2.13), as the equation (2.16) shows. The rotation θ_3, θ_4 and θ_5 are set to $[-180^o, 60^o]$, $[-45^o, 180^o]$ and $[-30^o, 145^o]$. Elements from the first row and third column are chosen.

$$\begin{gathered} e^{\hat{\omega}_4\theta_4}e^{\hat{\omega}_5\theta_5}e^{\hat{\omega}_6\theta_6} = (e^{\hat{\omega}^r_{ch}\theta^r_{ch}})^{-1}e^{\hat{\omega}^r_{up}\theta^r_{up}} \\ \prod_{i=4}^{6} e^{\hat{\omega}_i\theta_i} = \begin{bmatrix} c_5s_6 & c_5c_6 & -s_5 \\ -c_4s_6 - c_6s_4s_5 & c_4c_6 - s_4s_5s_6 & -c_5s_4 \\ -s_4s_6 + c_4c_6s_5 & c_6s_4 + c_4s_5s_6 & c_4c_5 \end{bmatrix} \end{gathered} \tag{2.16}$$

2.4.3 Calculation of Elbow Joint Rotation θ_7, θ_8

Similar with the calculation of joint angles in shoulder joint, relative orientation in elbow can be obtained by the equation (2.14), as the equation (2.17) shows. The ranges of rotation θ_7 and θ_8 are set to $[-10^o, 160^o]$ and $[-90^o, 90^o]$. The orientation measurement of upper arm and lower arm would generate slight bias due to surface skin movement, which could change the rotation matrix with two DoFs to three DoFs. Therefore the element denoting sine and cosine value would be normalized to reduce its effect before being applied to calculate the joint rotation.

$$e^{\hat{\omega}_7\theta_7}e^{\hat{\omega}_8\theta_8} = (e^{\hat{\omega}^r_{up}\theta^r_{up}})^{-1}e^{\hat{\omega}^r_{low}\theta^r_{low}}$$

Table 2.1: Assessment of Joint Angle Error

Rotation	θ_1	θ_2	θ_3	θ_4
Mean	4.83^o	0.37^o	-0.20^o	2.09^o
Variance	2.87	1.85	1.54	3.61
Rotation	θ_5	θ_6	θ_7	θ_8
Mean	0.76^o	-3.54^o	-0.94^o	-1.55^o
Variance	4.75	5.48	3.68	2.95

$$e^{\hat{\omega}_7\theta_7}e^{\hat{\omega}_8\theta_8} = \begin{bmatrix} c_8 & s_8 & 0 \\ -c_7 s_8 & c_7 c_8 & -s_7 \\ -s_7 s_8 & c_8 s_7 & c_7 \end{bmatrix} \tag{2.17}$$

2.5 Experiments

Since joints' position and rotation are mathematically related, we select joint rotation to evaluate the performance of this motion tracking system by comparing it with the Optitrack, one optical tracking system. The IMU sensors utilized in the experiments are commercial products APDM which are capable of accurately measuring acceleration, angle velocity and orientation. All the IMU sensors shares the same global frame determined by the magnetic field and the gravity field. Both of the devices are working at 80 Hz. The configuration of Optitrack and the proposed system is shown in Figure 2.2. Two participants are involved in the experiments. In the initialization process, participants are required to stand straight with their arms vertical to the ground and then do shoulder's pronation and supination rotation to help determine the body frame. In the experiment part, they are asked to sequentially perform the movements respectively related with waist joint, shoulder joint and elbow joints to achieve clear joint rotation. All the movements are continuously repeated multiple times. After the performance, collected data from IMU system and Optitrack are imported into PC for further analysis.

The joint angles tracked by both systems are segmented and extracted according to their movements. The comparison is shown in Figure 2.3 where the red dash line

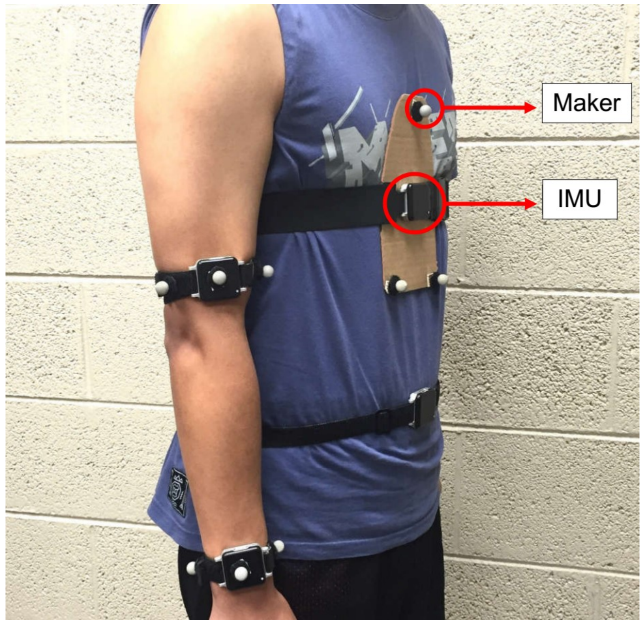
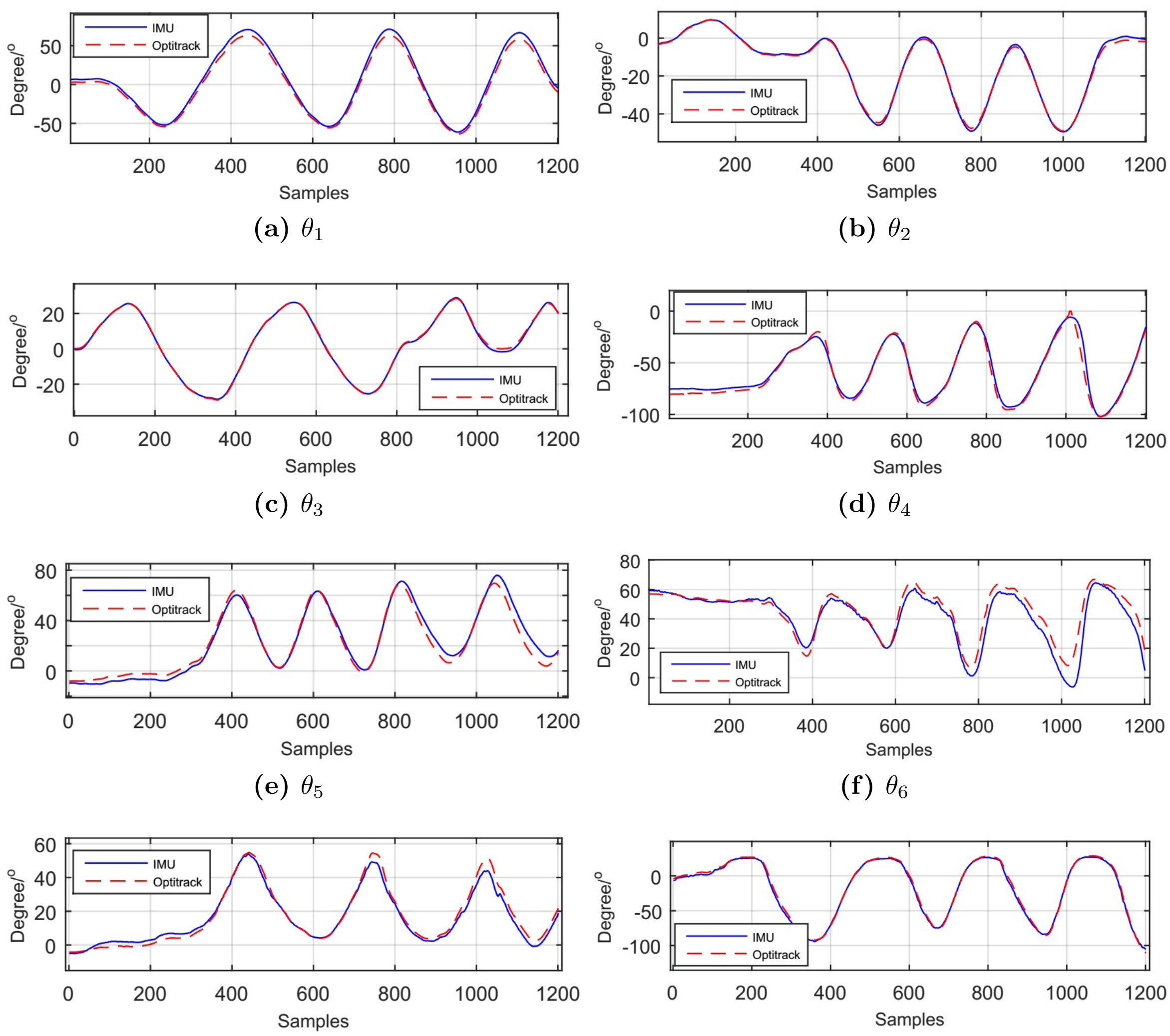


Figure 2.2: Configuration of IMUs and Optitrack

represents results of Optitrack and the blue line represents results of IMU system. Mean and standard variance are used to assess system's accuracy. The assessment shown in table 2.1 indicates this system has a high accuracy. It also shows that different performance exist each joint rotation, which is mainly due to the soft tissue artifact. Compared with other body segments, trunk has less intensive motions, which causes less soft tissue displacement during its kinematic measurement. Therefore, the estimation of wait joint's rotation exhibits better results. Joint rotations θ_4, θ_5 and θ_6 in the shoulder joint shows bigger system errors. That is mainly because the biceps muscle would affect IMU sensors' orientation and position during its contraction and relaxation. Since the kinematic estimation of elbow joint is related to the sensor on upper arm, rotations θ_7 and θ_8 are also affected.

To intuitively analyze motions' kinematics, participants' movements are reconstructed using estimated joint position. Figure 2.4 shows one frame of movements of trunk and right upper limb. The joint's coordinates are expressed in the body frame.



(a) θ_1 **(b)** θ_2 **(c)** θ_3 **(d)** θ_4 **(e)** θ_5 **(f)** θ_6 **(g)** θ_7 **(h)** θ_8

Figure 2.3: Comparison of Joint Angles from IMU System and Optitrack

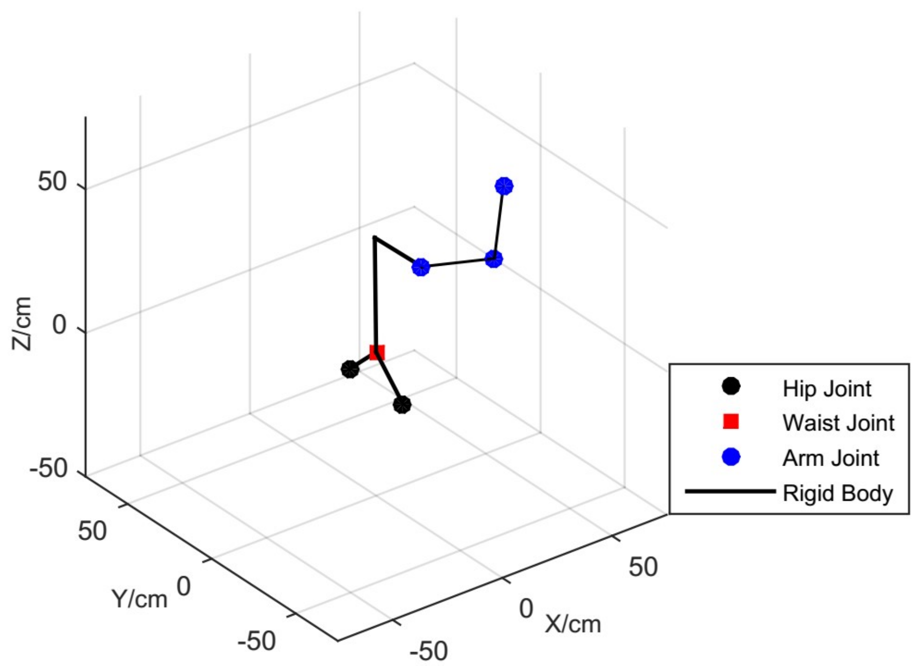


Figure 2.4: Motion Reconstruction

2.6 Conclusion

In this paper, an inertial-based motion tracking system is demonstrated. Experimental results verifies its capability of accurately estimating joints' position and rotation in the arbitrary movements with high degree DoFs. A kinematic model for robot arm is first designed to help describe upper extremity and trunk. Based on this model, twist and exponential map technology could efficiently estimate joints' kinematics by analyzing the relation between sensors' orientation and joints' rotation. Since this system only considers relative kinematics with respect to the initial configuration, IMU sensors' predefined position and orientation during sensor mounting would become unnecessary, which increases accuracy's stability. The initialization process is also simple and easily conducted. These advantages make this system a suitable tool to monitor patient's rehabilitation from motor deficit disease in the home-based environment.

Bibliography

Anderson, C., Rubenach, S., Mhurchu, C. N., Clark, M., Spencer, C., and Winsor, A. (2000). Home or hospital for stroke rehabilitation? results of a randomized controlled trial i: Health outcomes at 6 months. *Stroke*, 31(5):1024–1031. 4

Chen, X., Zhang, J., Hamel, W. R., and Tan, J. (2014). An inertial-based human motion tracking system with twists and exponential maps. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 5665–5670. IEEE. 6

Cooper, G., Sheret, I., McMillian, L., Siliverdis, K., Sha, N., Hodgins, D., Kenney, L., and Howard, D. (2009). Inertial sensor-based knee flexion/extension angle estimation. *Journal of biomechanics*, 42(16):2678–2685. 5

El-Gohary, M. and McNames, J. (2012). Shoulder and elbow joint angle tracking with inertial sensors. *Biomedical Engineering, IEEE Transactions on*, 59(9):2635–2641. 6

Favre, J., Jolles, B., Aissaoui, R., and Aminian, K. (2008). Ambulatory measurement of 3d knee joint angle. *Journal of biomechanics*, 41(5):1029–1035. 5

Giansanti, D., Maccioni, G., and Macellari, V. (2005). The development and test of a device for the reconstruction of 3-d position and orientation by means of a kinematic sensor assembly with rate gyroscopes and accelerometers. *IEEE transactions on biomedical engineering*, 52(7):1271–1277. 5

Go, A. S., Mozaffarian, D., Roger, V. L., Benjamin, E. J., Berry, J. D., Blaha, M. J., Dai, S., Ford, E. S., Fox, C. S., Franco, S., et al. (2014). Heart disease and stroke statistics–2014 update: a report from the american heart association. *Circulation*, 129(3):e28. 4

Lundberg, A., Svensson, O., Nemeth, G., and Selvik, G. (1989). The axis of rotation of the ankle joint. *Journal of Bone & Joint Surgery, British Volume*, 71(1):94–99.

Murray, R. M., Li, Z., Sastry, S. S., and Sastry, S. S. (1994). *A mathematical introduction to robotic manipulation*. CRC press. 10

Norkin, C. C. and White, D. J. (2009). *Measurement of joint motion: a guide to goniometry*. FA Davis. 13

Pérez, R., Costa, Ú., Torrent, M., Solana, J., Opisso, E., Cáceres, C., Tormos, J. M., Medina, J., and Gómez, E. J. (2010). Upper limb portable motion analysis system based on inertial technology for neurorehabilitation purposes. *Sensors*, 10(12):10733–10751. 6

Wu, G., Van der Helm, F. C., Veeger, H. D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., et al. (2005). Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motionpart ii: shoulder, elbow, wrist and hand. *Journal of biomechanics*, 38(5):981–992. 7

Yun, X. and Bachmann, E. R. (2006). Design, implementation, and experimental results of a quaternion-based kalman filter for human body motion tracking. *IEEE transactions on Robotics*, 22(6):1216–1227. 5

Zhou, H., Stone, T., Hu, H., and Harris, N. (2008). Use of multiple wearable inertial sensors in upper limb motion tracking. *Medical engineering & physics*, 30(1):123–133. 5

Vita

Xiaodong Yang was born in Anyang, Henan, China, to the parents of Jushan Yang and Chunge Zhao. He attended NO.1 Senior Middle School Puyang in China, After graduation. He headed south to the University of Electronic, Science and Technology of China where he Obtained a Bachelor Degree in Mechanical Engineering in 2014. he headed for the University of Tennessee, Knoxville, USA in 2014 for his graduate study in master degree. He accepted a graduate research assistantship from the Department of Mechanical, Aerospace and Biomedical Engineering. He graduated with a master of science degree in Mechanical Engineering in December, 2016.